Engineering Geology 201 (2016) 45–56

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Wave propagations through jointed rock masses and their effects on the stability of slopes

Ailan Che *, Hongkai Yang, Bin Wang, Xiurun Ge

School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200030, China

ARTICLE INFO

Article history:
Received 22 June 2015
Received in revised form 14 December 2015
Accepted 19 December 2015
Available online 23 December 2015

Keywords:
Rock slope
Wave propagation
Discontinuity
Shaking table tests
Seismic stability

ABSTRACT

Seismic behavior in rock slopes with discontinuities is largely governed by the geometrical distribution and mechanical properties of the discontinuities. Particularly, high and steep rock slopes, which are dominated by bedding and toppling discontinuity joints, are likely to collapse and cause serious damage to structures near the slopes. Because the composition of geological materials and discontinuities becomes more complex, and depending on the specifics of the ground motion caused by the earthquake, slope stability becomes very complicated under earthquake loadings. Special attention should be paid to the study of wave propagation phenomena in rock masses and their effects on the stability of rock mass slopes. This research first focuses on the analysis of the wave propagation phenomenon using numerical methods. The wave propagation characteristics in rock mass slopes with bedding and toppling discontinuity joints are assessed using two-dimensional, dynamic FEM analyses. An analytical result is obtained in the time domain and allows one to consider multiple wave reflections between joints. Next, a series of shaking table tests are conducted on a scaled model of a high and steep rock slope with bedding discontinuity joints. The shaking table tests are performed to evaluate the influence of wave propagation on the stability of the slope. These tests show that an amplification area will form at the top of the slope. When the amplitude of the input acceleration reaches a certain value, an area at the top of the slope completely collapses along a slide surface, which is simulated using Teflon tape in the experiments.

1. Introduction

An 8.0 Ms Wenchuan earthquake occurred on May 12, 2008, in the Sichuan province of central China. The epicenter is close to the Longmen Mountain region. This earthquake not only caused extensive damage to rural houses, educational and health care facilities, and lifeline engineering systems but also induced an abundance of landslides and other geologic disasters, such as collapses, debris flow, and shattered mountains (Li and He, 2009). In the field surveys of geological disasters after the earthquake, we observed that several large stones on a peak of Shizi Hill in Qingchuan County near the epicenter of Wenchuan were moved and rotated after the main shock. This indicated that the vertical acceleration at the peak was very strong, exceeding 1000 gal (Xu and Huang, 2008). In general, rock masses on slopes are collapsed by P- and S-waves. First, rock masses on the slopes are shaken vertically and lateral cracks are induced on the slope surface by P-waves. This weakens the rocks and slope stability. Second, landslides and collapses are induced by the strong horizontal shaking from S-waves. Field investigations in the damaged areas showed that the fractured surfaces of landslides are characterized by rough and serrate shapes. These features are quite different from those of non-earthquake-induced landslides, which have smooth, curved surfaces. It is generally considered that rough and serrated fracture surfaces are formed by earthquakes. Fig. 1 shows, a nearly vertical back edge with a rough and serrated fracture plane (Yin, 2009) at the landslide in the village of Dongjia in Qingchuan County. Most of the landslides near the epicenter of the Wenchuan earthquake were subjected to strong lateral S-wave forces and were characterized by “throw-like collapses”. Given the phenomena that drive the slide body, there is an area where the original geomorphology does not change and ground vegetation does not have any relicts. In this case, the slide body can be considered to be “thrown out” with certain acceleration by the S-waves, and the thrown area is called the “slide-out area” (Fig. 2). Around large sliding bodies, numerous heavy stones (tens to hundreds of tons) have been thrown away by tens to hundreds of meters because of the earthquake. We can see such throwing stones in the town of Yingxiu, which was the epicenter of the earthquake. A heavy stone (~300 t) was thrown out from the top of a steep cliff over a highway to the outside pavement. The horizontal acceleration of the heavy stones was estimated to be approximately 1400 gal based on field observations and a preliminary analysis (Yin, 2008).

Sliding and collapse during earthquakes are the main forms of geological disasters on slopes, and the dynamic stability of slopes has been

* Corresponding author at: Dongchuan road 800, Shanghai 200030, China. Tel.:/Fax. +86 21 34206564.
E-mail address: alche@sjtu.edu.cn (A. Che).

http://dx.doi.org/10.1016/j.enggeo.2015.12.018
0013-7952/

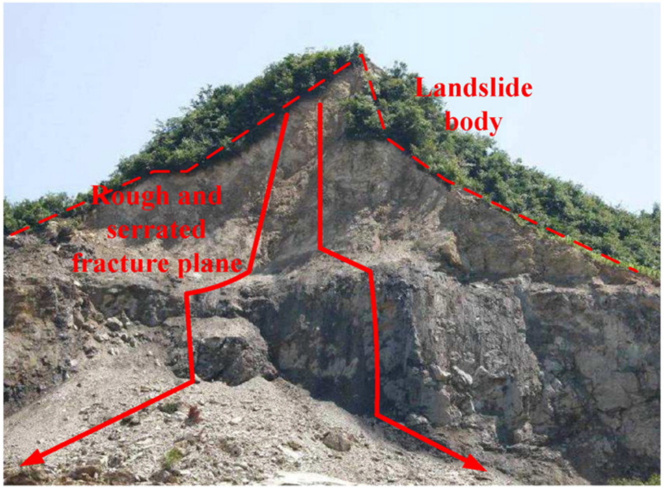

Fig. 1. The landslide at Dongjia village Qingchuan County.

one of the most important topics in geotechnical and seismic engineering. The failure modes of rock slopes predicted by simple models are shown as plane sliding, wedge sliding, toppling or some combinations of these modes (Goodman, 1989). However, given the complexity of the slope compositions and discontinuities in geological materials, and given the nature of earthquake-induced ground motion, it is difficult to quantitatively assess failure potentials (Hudson and Harrison, 1997; He and Liu, 1998; Kumsar et al., 2000). It is well known that rock joints and discontinuities play an important role in wave propagations (Crampin, 1984; Schoenberg and Douma, 1988). Wave propagation in rock masses and its influence on slope stability have become some of the most important topics in rock dynamics and earthquake engineering.

The propagation of seismic waves in jointed rock masses can be modeled by assuming the medium to be continuous or discontinuous. Many numerical methods are available for studying rock engineering issues. These methods are very useful for solving more complex but realistic problems that could not be solved using traditional approaches. Additionally, there are both continuous and discontinuous; medium numerical methods to analyze the wave propagation and seismic stability of rock masses. The continuous medium numerical methods include the finite flement method (FEM) (Goodman et al., 1968; Pande et al., 1990; Matsui and San, 1992; Schwer and Lindberg, 1992), the finite difference method (FDM) (Schwer and Lindberg, 1992) and the boundary element method (BEM) (Crotty and Wardle, 1985) and their combined methods (Beer, 1986). These methods consider discontinuities such as faults, joints, and cracks in the rocks as special joints elements. The discrete element method (DEM) is a useful discontinuous medium numerical method (Cundall, 1971), that models the rock mass as an assemblage of rigid or variable blocks cut by faults, joints and cracks interacting with one another. Discontinuous deformation analysis (DDA) is a type of discrete element method originally proposed by Shi, 1988. DDA adopts a stepwise approach to solve for the large displacements that accompany discontinuous movements between blocks; it is capable of simulating discontinuous problems like jointed rock slopes (Shi and Goodman, 1988). The numerical manifold method (NMM) and meshless method offer the possibility of a discretized approach without the entanglement of the mesh (Zhu et al., 2011; Zhuang et al., 2014a, 2014b). There are remarkable successes reported in applying these methods for analyzing challenging engineering problems (Zheng et al., 2014; Zhuang et al., 2014c). To model rock fractures, Ngo and Scordelis (1967) proposed a two-node linkage element to represent a rock joint. As an improvement, based on the lumped interface, Goodman et al. (1968), Goodman, (1976) proposed a joint element for the FEM. The Goodman joint element is a linear line element suitable for 2D analysis with four nodes and no thickness. The stiffness matrix for the joint element is derived in the same way as that for the regular finite element method. Mehtab and Goodman (1970) extended the formulation of the Goodman joint element to a 3-D solution.

The problem of wave propagation in discontinuous media has been studied by many authors (Achenbach and Li, 1986a, 1986b; Roy and Pyrak-Nolte, 1995) but the analysis of the effects of multiple reflections between the joints has not been widely discussed. Moreover, the influence of the dynamic loads on the rock mass slope has not been extensively investigated either. Given these facts, a better understanding of wave propagations in rock masses and their effects on the stability of the rock mass slope are needed.

In order to clarify the effects of the discontinuity joints on the wave propagation characteristics in rock mass slopes, two-dimensional dynamic FEM analyses with bedding, toppling joints and its combined distribution are performed. The dynamic response of the acceleration is studied, and the response in the time domain and peak ground acceleration are assessed. To evaluate the influence of wave propagation on the stability of the slope, a series of shaking table tests are conducted on a scaled model of a high and steep rock slope with bedding discontinuity joints. Teflon tape is used to simulate the discontinuity joint. The dynamic response of the acceleration compared with simulation results and failure mechanism is discussed.

2. Wave propagation characteristics of the rock mass slope with joints

FEM dynamic analyses were performed for wave propagations through rock masses with joints in two-dimensions. Abaqus/Explicit is chosen as the solver for its transient dynamics simulation capabilities (Abaqus Explicit User Manual). For effectively simulating wave propagations in a discontinuous medium, the size, degree of subdivision and

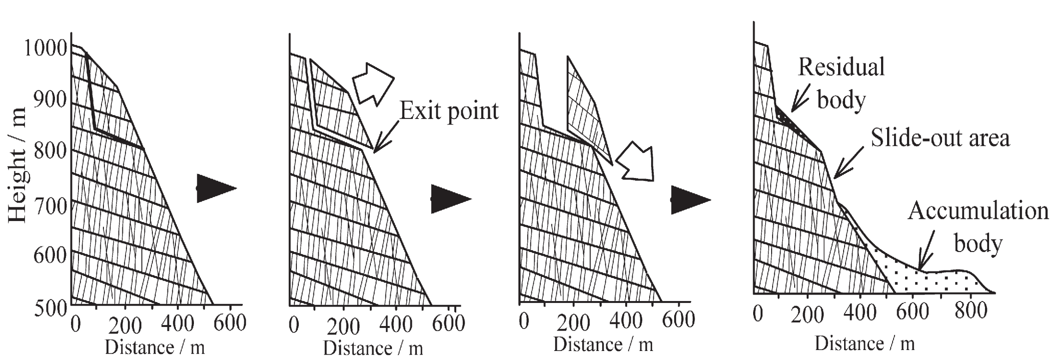

Fig. 2. Evolution process of landslide under the earthquake motions.